

**Annual Project Report**  
**“REAL-TIME GLOBAL EARTHQUAKE CHARACTERIZATION”**  
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## **Investigations**

In recent years, geologists and geophysicists have witnessed a revolution in the development and implementation of an array of new tools for measuring motions of the earth's crust, including global positioning satellites, interferometric synthetic aperture radar, and broadband digital seismic systems, allowing tremendous advances in motion detection accuracy. Japan and Taiwan took the lead in the installation of these instruments and the recent Chi-Chi, Taiwan earthquake ( $M_w = 7.7$ ) has produced a remarkable set of data. As demonstrated in this proposal, we can successfully model the near-in data (GPS and strong motions) with far-fewer parameters than reported to date using our recently developed analytical tools (wavelet transforms, modified annealing, etc.). Fewer parameters increase uniqueness and in this case allowed an accurate prediction of the teleseismic data (P and S waves) using only near-in data. Loading this source description into a 3D earth model (SEM code by *Tromp et al.* (2000), assuming Ritsema's tomographic model with Mooney's crust) produced a remarkable fit of over 200 IRIS stations at periods greater than 15 secs. This same source description fits the strongest observed motions in displacement (8 meters), velocity (3 meters/sec), and filtered acceleration ( $260 \text{ cm/sec}^2$ ) with a 2-parameter rise-time lasting 6 secs. *Wald et al.* (1991) produced similar strong motion estimates for the 1906 San Francisco earthquake by comparing observations at the same stations with the Loma Prieta earthquake. Most structures in San Francisco could not take these kinds of motions (Paul Jennings, personal communication) and, therefore, it is essential to learn more about the level of strong shaking for modern large events where near-in seismic data is not available but a combination of global and static data can be used to estimate strong shaking. Moreover, a rapid assessment of earthquake damage following major global events proves very useful in providing emergency services by the various agencies. We plan to address these problems by working with a USGS team of researchers to develop the software necessary for simulating analytical shakemap for significant events. We plan to exploit the Global IRIS Network data at all ranges to use in conjunction with GPS, InSAR, and other optical fault-trace imaging techniques to predict the local strong motions. Thus, the input parameters include the IRIS seismic data, strong motions (if any), geodetic and field geology, etc. The output would be produced in phases:

- Phase 1, distributed rupture model and analytical shakemap (hour)
- Phase 2, updated by adding new data, geodetic, etc. (day or two)

## **Results:**

- (1) Abstract by Chen Ji, Dave Wald, and Don V. Helmberger
- (2) Abstract by Chen Ji, Don V. Helmberger, Dave J. Wald, and Kuo-Fong Ma
- (3) Abstract by Chen Ji, Don V. Helmberger, and Jeroen Tromp
- (4) Abstract by Chen Ji, Don V. Helmberger, and David Wald

## **Quick Finite-Fault Inversion and Strong Motion Prediction: Feasibility, Process, and Developments**

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As part of a larger, concerted effort to rapidly assess the impact of major earthquakes globally and to provide input into other post-earthquake analyses (e.g., ground motions, stress changes, tectonic implications, etc.), we are developing and testing a new system to automatically determine finite-fault characteristics by inversion of teleseismic body waveforms. Although initially constrained from teleseismic data alone, which currently are the only rapid and reliable available data after major events worldwide, additional data will be used (either directly or as constraints) as they become available, including aftershock locations, geodetic displacements, and regional waveforms. Our ultimate goal is to provide well-constrained, estimated peak ground motions for input into a global ShakeMap, which in turn will allow automatic, reliable estimates of losses and overall impact. To evaluate the feasibility of such a system, we inverted for slip variations on a single plane for the 1999 Chi-Chi (M7.6) earthquake using only teleseismic data and then compared the 2-sec peak ground velocity map predicted by this model with the observations (constrained by over 400 stations). Even though the fault geometry of this earthquake was more complex than our simple approximation, as would be the case for our initial, automated solution, the predicted map matches the overall observed amplitude variations. While successful in that case, a fully automated system requires overcoming additional, significant hurdles, many of which we are discovering and addressing as we develop the processing system. One such hurdle addressed was the choice of the causative rupture plane from the two nodal planes of a moment tensor solution. We simply conduct finite fault inversions on the two planes simultaneously, and select the solution with a smaller error function. This approach worked well for recent the 2003 Carlsberg Ridge earthquake (M7.6), for which the inverted result matches the trend and extent of its aftershock sequence. Among the more challenging hurdles is compensating for travel time anomalies within an automated system. Using the 2002 Denali earthquake as an example, we show the importance of this correction and how we calibrated the teleseismic path effects with proximal fore- or aftershocks. We also show how an improved fault geometry based on a high-resolution DEM map enhanced the solution. Finally, we discuss ongoing developments, further results, and plans for this system.

## **Slip history and dynamic implications of the 1999 Chi-Chi, Taiwan, earthquake**

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We investigate the rupture process of the 1999 Chi-Chi, Taiwan, earthquake using extensive near-source observations, including three-component velocity waveforms at 36 strong motion stations and 119 GPS measurements. A three-plane fault geometry derived from our previous inversion using only static data (*Ji et al.*, 2001) is applied. The slip amplitude, rake angle, rupture initiation time, and risetime function are inverted simultaneously with a recently developed finite fault inverse method that combines a wavelet transform approach with a simulated annealing algorithm (*Ji et al.*, 2002b). The inversion results are validated by the forward prediction of an independent data set, the teleseismic P and SH ground velocities, with notable agreement. The results show that the total seismic moment release of this earthquake is  $2.7 \times 10^{20}$  N m and that most of the slip occurred in a triangular-shaped asperity involving two fault segments, which is consistent with our previous static inversion. The rupture front propagates with an average rupture velocity of  $\sim 2.0 \text{ km s}^{-1}$ , and the average slip duration (risetime) is 7.2 s. Several interesting observations related to the temporal evolution of the Chi-Chi earthquake are also investigated, including (1) the strong effect of the sinuous fault plane of the Chelungpu fault on spatial and temporal variations in slip history, (2) the intersection of fault 1 and fault 2 not being a strong impediment to the rupture propagation, and (3) the observation that the peak slip velocity near the surface is, in general, higher than on the deeper portion of the fault plane, as predicted by dynamic modeling.

## **Modeling Teleseismic P and SH Static Offsets for Great Strike-slip Earthquakes**

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Most body-wave modeling of earthquakes involves P and SH waves observed between  $30^\circ$  to  $90^\circ$ . Traditionally, only the "far field" contributions, whose waveforms are related to the moment-rate function  $M_t$ , are considered. The "near field" contribution, whose waveform is determined by the moment release function  $M_r$ , has generally been neglected. According to the "far field" approach, the displacements should ultimately become zero. However, in broadband records of recent large strike-slip events, such as the 2001 Kunlun and 2002 Denali earthquakes, displacement offsets of up to two thirds of the peaks of the P and SH phases are maintained until they are disturbed by the later arriving PP or SS phases. Hence, "near field" contributions must be included when we study the source processes of such events. We investigate complete synthetic seismograms generated by three basic double-couple fault types:  $90^\circ$  strike-slip,  $90^\circ$  dip-slip, and  $45^\circ$  dip-slip using several numerical solutions. We find that for a shallow earthquake, a  $90^\circ$  strike-slip fault can excite large P and SH near field terms, while the other two fault types generate negligible amplitudes. Our theoretical analysis indicates that this observation is entirely controlled by the source excitation characteristics. More importantly, the amplitude ratio of the "far field" to the "near field" is roughly proportional to the reciprocal of the shear velocity at the hypocenter. Hence considering "near-field" contributions provides unique constraints not only on the entire strike-slip component of fault-slip, but also on the down-dip extension of the rupture. While the "near field" terms are important, it is computationally difficult to generate high-frequency Green's functions at teleseismic distances using normal-mode or spectral-element (SEM) methods. The reflectivity method also fails to produce the near field term of the P waves due to the inaccurate earth-flatten approximation. Therefore, we develop a ray-based algorithm using "near-field" source excitation coefficients and correcting for the geometrical spreading in the spherical earth with normal-mode synthetics. Broadband synthetics generated based upon this new method compare favorably with SEM simulation. The new approach is used to study the source process of the 2002 Denali earthquake along with local strong motion and GPS observations.

## **A teleseismic study of the 2002 Denali, Alaska, earthquake and implications for rapid strong motion estimation**

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Rapid slip histories for the 2002 Denali, Alaska, Earthquake were derived from the global teleseismic waveform data. Three models indicates a step-wise improvement in matching the waveform data and in recovery of the rupture details by applying the wavelet inversion procedure discussed in [Ji *et al.*, 2002a]. The first model, referred to as Phase I, is analogous to an automated solution where a simple fault plane (300 km long) is fixed based on the preliminary CMT (Harvard) mechanism and assuming the PDE epicenter. The initial fits to the early portion of the P waves were poor since they do not display a strike-slip polarity pattern expected from the CMT mechanism. To improve this result, we first implemented a more realistic fault geometry using the Denali fault trace inferred from DEM topography in Phase II. While this produced some improvements, major waveform misfits still remained. We then calibrated path effects for P-wave and SH-wave arrival times using a comparably simple nearby foreshock, the 2002 Nenana, Alaska, earthquake. Time shifts of up to 4 sec for P waves and up to 8 sec for SH wave relative to *IASPEI91* travel-time table were found. Applying these corrections revealed some discrepancies in the rupture initiation. To produce a consistent picture requires at least 4 fault segments referred to as A, B, C and D. A weak rupture initiated on a strike-slip Denali fault branch A at a depth of 10 km where a low angle thrust fault plane B intersects A. After about 2 sec, a major event occurred on plane B (strike=221°, dip=35°) and dominated the rupture for the next 8 sec. When rupture B reached the surface, at about 10 sec after initiation, the major portion of the Denali fault (segment C) ruptured eastward with a relatively fast velocity (3 km/sec) producing a large slip concentration (up to 9 m at a depth of 10 km). The surface slip is about 7 m along a 30 km long segment. This feature is near the intersection of the Denali fault and the Totschunda fault (branch D). The rupture on D is relatively shallow (less than 15 km) while the extension beyond the intersection on the Denali fault displays deeper slip. The entire rupture extends over 90 sec and has an overall seismic moment of  $1.1 \times 10^{21}$  Nm with a centroid depth of 16.8 km. These models were used to predict the ground velocity and shaking intensity field in the fault vicinity. Peak velocities of over 2 m/sec occurred above the major surface offsets. The procedure using the teleseismic data to estimate local strong motions could be automated and used for global realtime earthquake shaking and damage assessment.